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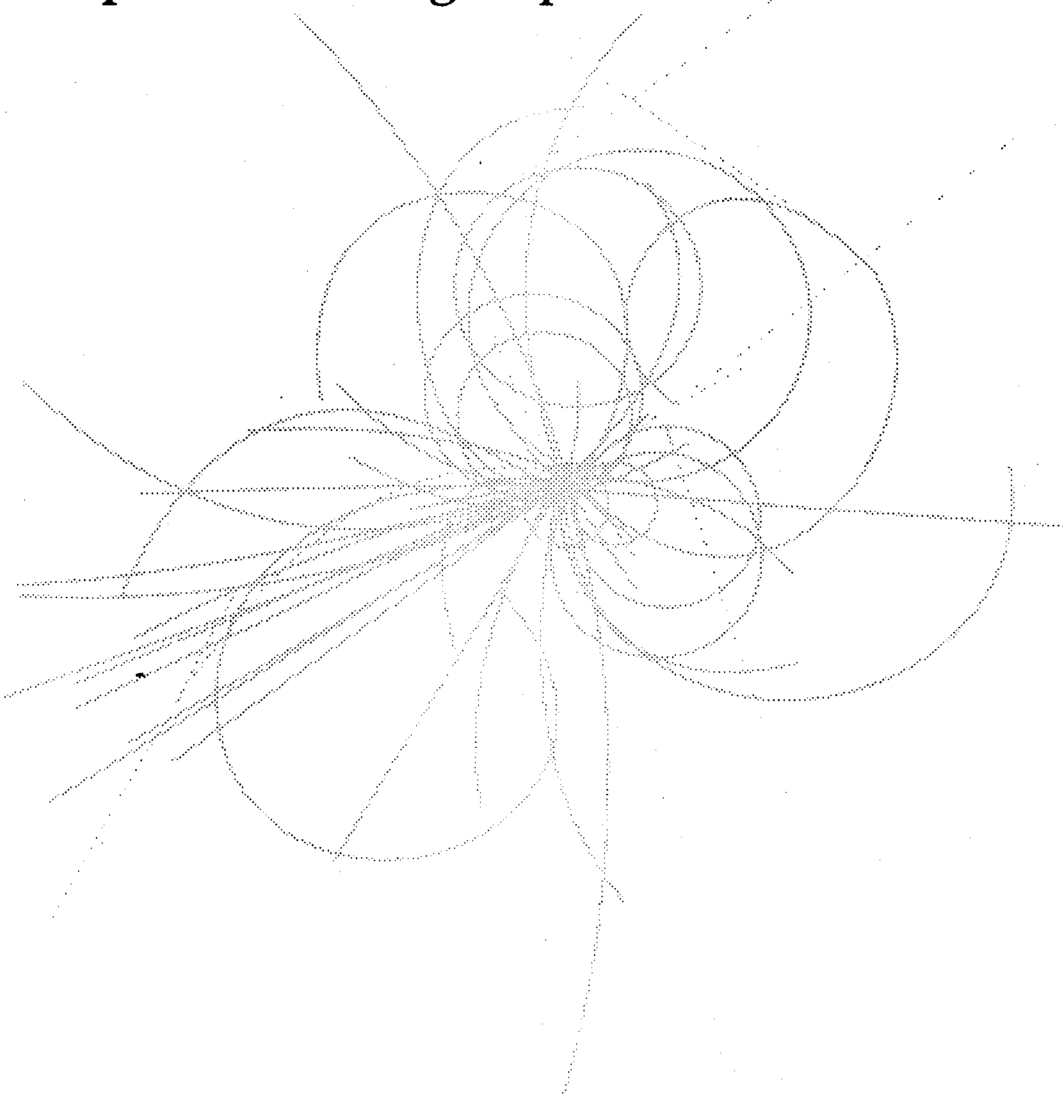

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RESULTS FROM A PARTIAL LIFETIME TEST OF A 40-MM-APERTURE, 17-M-LONG SSC MODEL DIPOLE

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ABSTRACT

A 40-mm-aperture, 17-m-long Superconducting Super Collider (SSC) model dipole was assembled at Brookhaven National Laboratory (BNL) and tested initially at Fermi National Accelerator Lab (FNAL) and later at BNL. At BNL an extended cycle test was devised to examine the magnet's performance through numerous cold tests and thermal

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cycles. This paper discusses the magnet's mechanical and quench performance and magnet field measurements during the tests.

INTRODUCTION

One area of interest in an SSC dipole magnet is in its performance during a test cycle approximating that which will be seen by an actual dipole within the collider. However, planning and carrying out such long tests on a magnet would require a great amount of time; therefore, test plans have been derived to examine a "Partial Lifetime" test for a collider dipole magnet. Such a test has been developed and carried out at BNL, and it has become known officially as the "Extended Cycle Test" (ECT).

In this paper we will discuss magnet DD0028, which completed the first ECT performed on a SSC dipole. Construction and magnet features will be reviewed first. Discussion will then turn to the test plan carried out at FNAL and BNL. Emphasis will be placed on number of quenches, power cycles, thermal cycles, etc., with comparisons to actual "Life Time" expectations of a collider dipole magnet. Finally, we will summarize quench performance, mechanical stability, and field quality along with any changes observed due to the extended period of testing on the magnet.

MAGNET FEATURES

DD0028 was constructed[3] with the conceptual cross section design designated C358D.[1,2] It is a 40-mm-aperture dipole magnet with a magnetic length of 16.6 m. The inner and outer conductors have copper-to-superconductor ratios (Cu:SC) of 1.3:1 and 1.8:1, respectively. The cables are wrapped in two layers of insulation, with the first layer being double wrap, 50% overlap, 1-mil Kapton. The second layer is a single wrap of 4-mil pre-pregnated fiberglass with an epoxy content of 24%.

The cables are then wound to form the inner and outer, upper and lower half of the coil. The coil ground insulation consists of Teflon (1 mil), Kapton (5 mil), strip heater (15 mil), and two more layers of Kapton (5 mil each). Mechanically seated shims are located at the poles, with the inner and outer coil shims being 25 and 32 mil, respectively.

The coils are collared using alternating left/right (spot-welded) Armco Nitronic 40 collars using the tapered key method. The collared coils are then placed in the yoke assembly, which consists of horizontally split modules. The long, straight section of the magnet consists of modules made of iron laminations, whereas the modules making up the end sections are stainless steel. The yoke assembly is then enclosed in a horizontally split stainless steel outer shell that is manually clamped together, then welded along the magnet's length.

The magnet is also fully instrumented with voltage taps and various strain gauge assemblies. Voltage taps, used for quench detection and analysis, are located on the quarter coil leads, on the inner-outer coil ("ramp") splice region, and on the first three turns at the pole of the inner coils. Special strain gauge collar packs are included to measure both the inner and outer coil stresses. Two packs are included, one at the location of the azimuthal high point in the coil size and the other at the corresponding low point. Four strain gauge assemblies (dubbed "bullets") are also located at the magnet's return end to measure the force that the coil exerts against the end plate.[4]

TEST PLAN

After assembly of the DD0028 cold mass at BNL, the magnet was transported to FNAL, where it was placed in a cryostat and run through the first series of tests. The test plan at FNAL consisted of cold testing followed by thermal cycling and retesting. During the cold tests, the magnet was brought to liquid helium temperatures, followed by initial cold electrical test prior to any quench testing. After all checks were complete, a series of quenches was performed at a rate of 16 A/sec to examine the magnet's quench performance. Quench testing continued until four conductor-limited quenches were established. Following quench testing, magnetic measurements were made. These typically included 2000-A axial scans, NMR/Hall measurements, time-dependence measurements, and magnetization loops. Once the cold test program was complete, the magnet was brought back up to room temperature, then recooled for more cold testing. After four cold test cycles at FNAL, the magnet was returned to BNL for further cold testing.

The test plan used at BNL—the Extended Cycle Test—consisted of weekly test cycles whereby quenches and quench performance would be observed, followed by a series of power cycles, strain gauge measurements, and magnetic measurements. Warm-ups and cooldowns were planned for the weekends for more efficient use of time.

The effect of "conditioning" on the magnet's training performance was also examined. Training occurs when a magnet quenches below its expected short sample limit and continues until a conductor-limited quench is established. These training quenches are usually energy-deposited quenches that occur when there is movement of the conductor within the collared coil assembly. These movements, coupled with frictional forces, tend to cause frictional heating that may lead to a quench. Conditioning is the procedure in which the magnet is cooled to a temperature lower than test temperature, and a series of excitations is done to a current of 6.8 kA, just above the operating current of 6.5 kA. The expectation is that if any coil movement is to occur within the magnet, it will occur at these lower temperatures where the added thermal margin may allow for movement of the collared coil assembly. The collared coils can then position themselves in an equilibrium position without quenching. Therefore, during 4.35-K quench testing, any large conductor motion has already occurred, and the chance of training during quench testing is reduced. To examine the effects of conditioning, alternate thermal cycles included a conditioning period.

TEST SUMMARIES

FNAL testing consisted of four thermal cycles, with cooldown schemes shown in Table 1.

Table 1. Cooldown Schemes in FNAL Testing.

Cooldown	Restricted	Unrestricted	Conditioning
1	X		X
2	X		
3		X	X
4		X	

Restricted cooldowns consisted of lowering the magnet's temperature while maintaining a given temperature rise across the magnet. The ΔT restriction at FNAL was 125 K. During unrestricted cooldowns the ΔT restriction is removed, and the magnet is cooled to 4.3 K as quickly as possible. Cooldown times for restricted cooldowns are generally around 24–32 hours, while unrestricted cooldowns are approximately 12–14 hours. A summary of the four test cycles is shown below:

Quench Testing (47 total quenches):

1) initial quench during conditioning.
2) 27 quenches at 4.35 K.

BNL's ECT consisted of eight full test cycles, with conditioning beginning with the first thermal cycle, then alternating between thermal cycles. Test summaries are shown below:

Quench Testing (46 total quenches):

1) 31 quenches at 4.35 K with Cold Bore Tube.
2) 15 quenches at 4.35 K with Warm Bore Tube.

Power Cycles (100 A → 6500 A → 100 A):

1) 997 total at a rate of 100 A/sec (4.35 K).
2) 1332 total at a rate of 200 A/sec (3.85 K).

Prior to the last thermal cycle of cold testing at 4.3 K, the magnet was cycled eight times between a temperature of 300 K and 77 K, where 90% of the thermal contraction takes place. This was done to examine the effect of multiple thermal contractions and expansions on the mechanical and quench performance.

The totals from the partial lifetime test results include: 2329 magnetic cycles (25%), 20 thermal cycles (67%), and 93 total quenches (62%). Percentage of lifetime durability requirements are indicated in parentheses.

QUENCH TEST RESULTS

To examine the magnet quench behavior, the magnet's temperature is lowered to 4.3 K and energized at a rate of 16 A/sec until the magnet quenches. This is repeated until a plateau of four quenches is obtained. Plateau quenches are typically conductor-limited quenches, with quench currents remaining stable from one quench run to the next. Figure 1 shows a summary of the quenches conducted on DD0028 throughout its test history.

Influence of Conditioning

During the first conditioning cycle at FNAL, the magnet quenched on one of the excitations to 6800 A. Following a warm-up to 4.35 K, the magnet exhibited one further training quench, then attained plateau for the remaining quenches. After completion of the first thermal cycle, training was observed in each test cycle where conditioning was left out. In no thermal cycle where conditioning was done was there any training. It therefore appears that an initial conditioning cycle prior to quench testing improves the training performance of the magnet following a thermal cycle.

Plateau Quench Currents and Origins

The quench currents and origins showed good stability throughout the testing at both labs. All FNAL plateau quench origins were located in the pole turn, right straight section, upper inner coil, near the middle of the magnet, while BNL quench origins were located similarly in the lower inner coil. These plateau quenches occurred at the region in which the field is at a peak, as expected for conductor-limited quenches. Differences in quench locations between FNAL and BNL data could be attributed to differences in cryogenic conditions during testing. Helium flow rates at FNAL were approximately 45–50 g/sec, whereas BNL flow rates were 160–165 g/sec.

Plateau quench currents from one thermal cycle to the next also showed good stability. There was no indication of decreased quench performance and, therefore, no signs of degradation of the conductors from thermal cycle to thermal cycle.

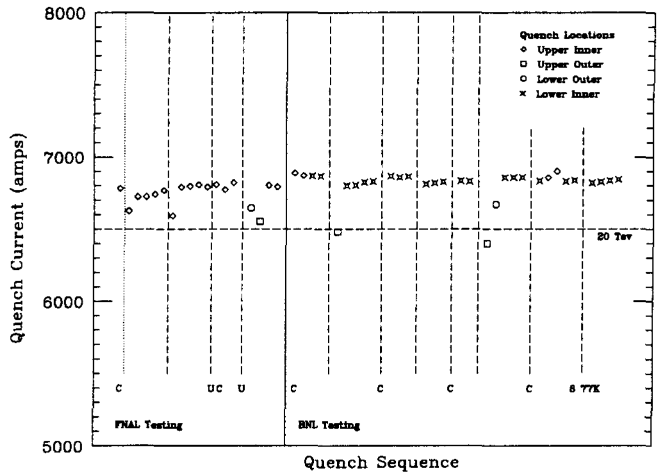

Figure 1. Quench history of DD0028. Conditioning cycles indicated by "C," unrestricted cooldown by "U."

MECHANICAL TEST RESULTS

Inner and Outer Coil Stress Histories

Figures 2 and 3 show the inner and outer coil stress as measured during different stages of testing. For each thermal cycle of testing, a set of 10 strain gauge reads are made with zero current on the magnet prior to cooldown, after cooldown, and again prior to warm-up. The figures show the average of these 10 reads for each initial warm, initial cold, and final cold reads for a test cycle. Indicated in the plot is also the point at which the temperature was cycled eight times between 300 K and 77 K.

The initial reads prior to any testing indicate that the magnet was assembled with similar levels of inner and outer coil stress and that the change in prestress throughout testing decreases slightly from start to finish. The inner coil stress shows a loss of approximately 8 MPa in prestress, while the outer shows a loss of 2 MPa in prestress by the time the last warm reads are made.

During cooldown, both the inner and outer coils exhibit a loss in prestress of 40% and 39%, respectively. This loss in prestress remains fairly stable throughout testing, leaving consistent and acceptable levels of coil stress at 4.3 K. Coil stress values showed only slight decreases during excitation, with 4 MPa observed for the inner coils and the outer coils remaining stable. It is also observed that the coil stresses show further decreases with testing, which is evident in the final cold reads of each test cycle. The inner coils show a decrease in each cycle (except for three cycles), while a decrease is seen in each cycle for the outer. These further decreases in coil stresses during testing at 4.3 K typically occur during the first few excitations of the magnet to high fields; thereafter they remain stable.

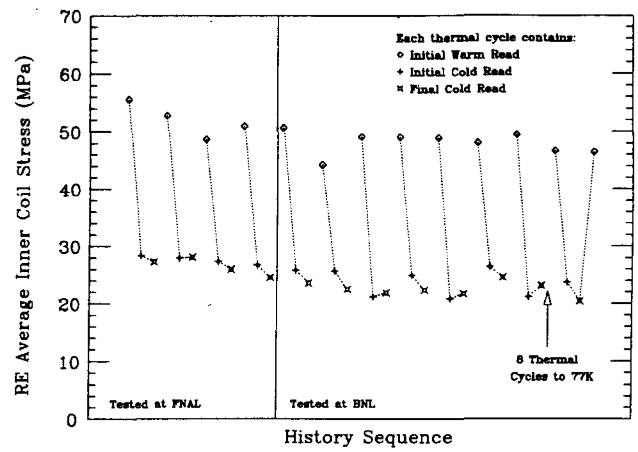

Figure 2. Inner coil stress history of return end gauge pack. Each thermal cycle contains an initial warm, cold, and final cold read.

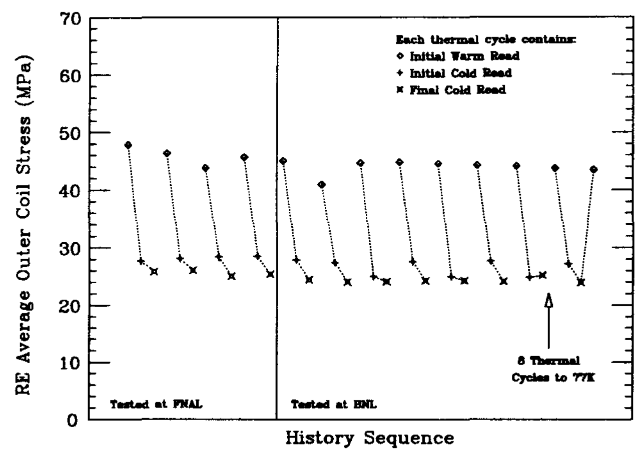

Figure 3. Outer coil stress history of return end gauge pack. Each thermal cycle contains an initial warm, cold, and final cold read.

End Force Histories

Figure 4 shows the total end force plotted in the same way as the inner and outer coil stress. For each thermal cycle of testing, the total end force prior to cooldown, following cooldown, and prior to warm-up are plotted for both FNAL and BNL data. Differences between FNAL and BNL data can be attributed to the horizontal test setup at BNL. During setup of the test stand, the bore tube is welded to the extension bellows at both the lead and return end. Following this welding, it is observed that the end force increases. This has also been observed in previous magnets tested, where reads taken prior to setup show lower values of end force than those after welding. Therefore, it is not believed that these differences in end force observed between the two labs are due to either transportation or to an error in the calibration.

The initial end force levels prior to cooldown for each cycle show a considerable increase in the first three test cycles at FNAL, whereas the last six test cycles at BNL show end force levels that remain rather stable. This initial increase in end force is due to a "ratcheting" effect that takes place during cold testing. This is seen by comparing the initial cold reads with the final cold reads of each test cycle. During testing, it is observed that for each excitation of the magnet to high fields, there is a corresponding increase in end force. This increase typically occurs following the first few excitations, after which the magnet remains stable through the test cycle. Ratcheting occurs when the magnet is excited to high fields, where the Lorentz forces tend to expand the coils radially and axially outward. When the current is brought down to zero, the collar-yoke interference tends to "hold" the collared coil assembly at the position it reached during excitation rather than allowing it to return to its original configuration prior to excitation. Therefore, an increase in end force is observed. As mentioned above, this increase is observed only after the first few excitations during a test cycle.

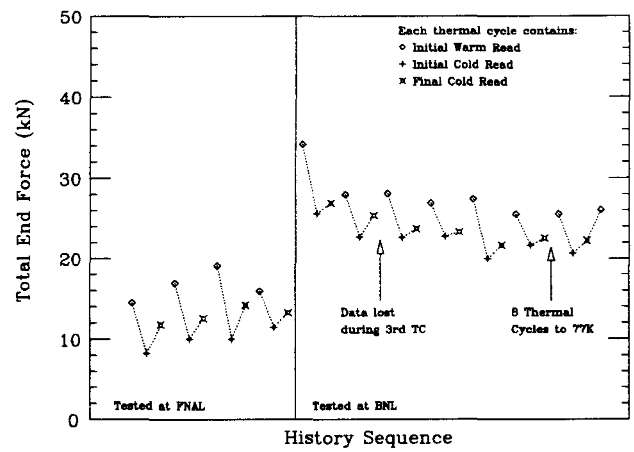

Figure 4. Total end force history of the return end. Each thermal cycle contains an initial warm, cold, and final cold read.

MAGNETIC MEASUREMENT TEST RESULTS

Throughout the testing of DD0028, magnetic measurements were carried out in order to examine the effects of quench testing, power cycles, and thermal cycling on the multipole components of the magnetic field. An axial scan of the magnetic field was made with a rotating coil assembly known as a "MOLE" at a current of 2000 A following a pre-cycle to 6500 A. The coil is 1 m in length, allowing 17 positions along the magnet's length to be measured. The data obtained from the MOLE is used to calculate the normal and skew components of the magnetic field. Therefore, measurements taken from each thermal cycle can be examined for any changes that may occur throughout testing.

Generally, one focuses on the lower-order normal and skew terms of the magnetic field. These lowest-order terms, quadrupole and sextupole, typically show the largest effects due to construction errors and any changes that may occur after the original construction. Any deformations of the collared coil assembly that may occur throughout testing will therefore show up as a corresponding change in these terms.

Axial scans were done at FNAL before and after the initial quenching of the magnet. Axial scans were then repeated the following thermal cycle and in each thermal cycle during the ECT at BNL except for the sixth cycle. Axial scans that were done at BNL were followed up with a second scan in order to check the repeatability of the measurement. Figure 5 shows the sextupole component of the magnetic field for each axial scan. Each point represents the average along the magnet's length where the end regions and strain gauge collar pack locations have been excluded from the average. Differences between FNAL and BNL data can be attributed to the fact that different measuring devices were used. At FNAL, measurements were made with MOLE B1, while at BNL measurements were made with MOLE D1. Calibration of MOLEs B1 and D1 is necessary to resolve the question of whether it's really the MOLE or the magnet.

During the seventh thermal cycle, there is also an apparent shift in b_2 as compared to axial scans measured in the 5th and 8th thermal cycles. These scans were made using the same MOLE, and it is believed that the prior excitation loop caused a different initial b_2 for these runs.

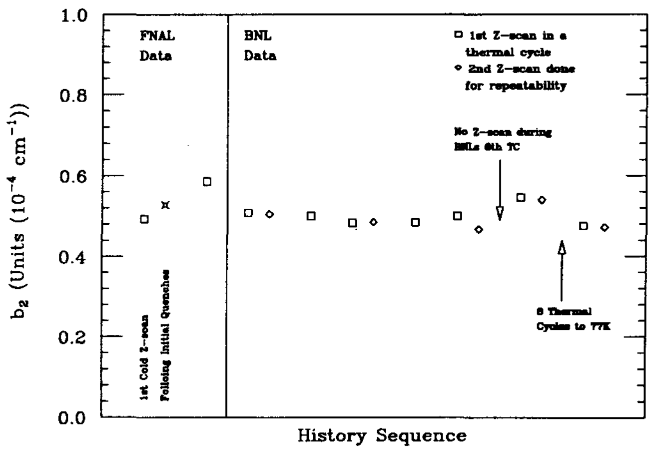

Figure 5. Sextupole history of DD0028. Each point represents an average taken along the magnet's length. End regions and strain gauge collar pack locations are omitted from the average.

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